

# Analysis of the Eruptive Event after the Solar Flare of June 7, 2011

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**Abstract**—We present the results of the analysis of the observational data for the eruptive event of June 7, 2011 obtained both on spacecraft (SDO, LASCO) and using ground-based solar instruments. The event was characterized by deceleration of the shock front during the first minutes of the evolution from 1150 to 710 km/s. According to the LASCO data, the velocity of the coronal mass ejection (CME) on time scales of more than an hour did not exceed 285 km/s. According to the spectral observations of the ground-based instrument, we found the radial velocities of the fastest features of the exploding prominence to be between 200 and 190 km/s. We paid special attention to studying the physical characteristics of a blob—a separate drop of coronal rain that accompanied the event. The line-of-sight velocity of the blob increased in 5 min from 207 to 263 km/s, its diameter was 5900 km, and the estimated mass was  $1.8 \times 10^{12}$  g; the values of temperature and turbulent velocity of 7880 K and  $V_{\text{turb}} = 18.7$  km/s were obtained, correspondingly. We should note that the finding and measurement of velocities were limited by the capabilities of narrow-band filters and a small wavelength range in most solar instruments. This paper is based on the report made at the conference “Ideas of S.B. Pikelner and S.A. Kaplan and Modern Astrophysics” (Sternberg Astronomical Institute, Moscow State University, February 8–12, 2021).

**Keywords:** solar flare, prominence, coronal rain, coronal mass ejection

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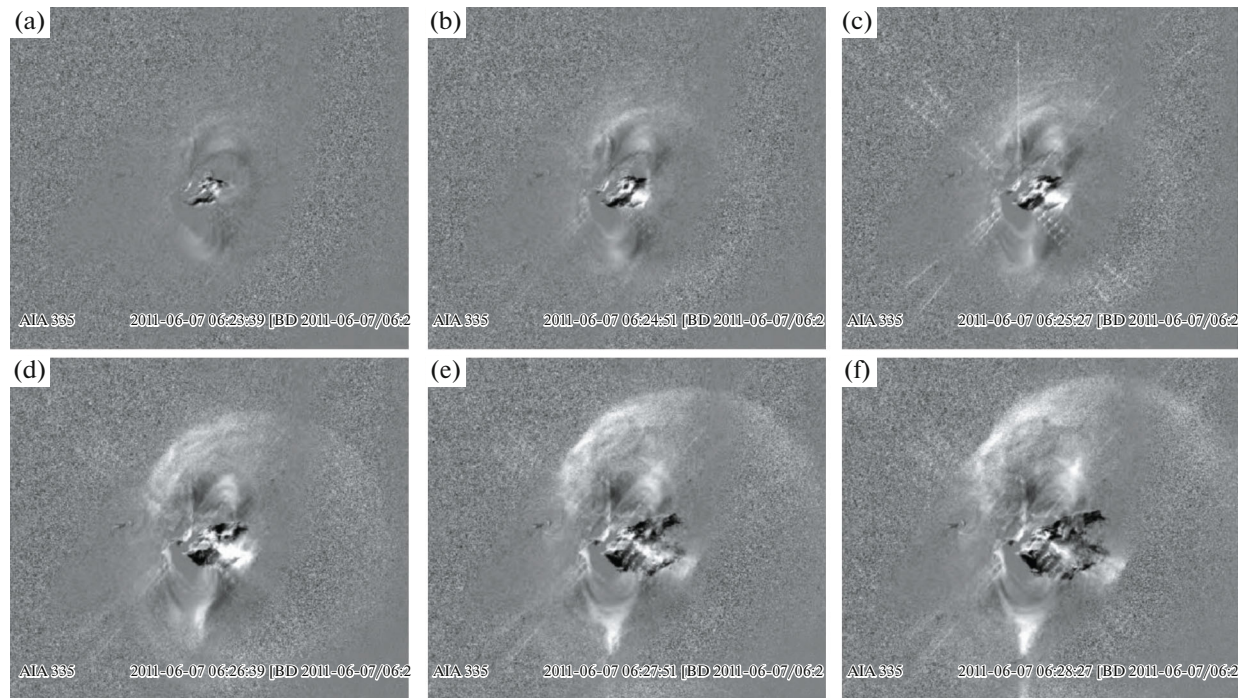
## 1. INTRODUCTION

Eruptive processes in the solar atmosphere consist of phenomena of various spatial and energy scales from strong coronal mass ejections (CMEs) to blobs — compact fragments of the ejection material that fell back into the chromosphere.

On June 7, 2011, a filament ejection occurred in the active region NOAA 11226, which was followed by an M2.5 flare and a strong CME. A part of the ejected dense material escaped into interplanetary space, while the other part fragmented and fell back into the chromosphere. The event was observed by space instruments (SDO, STEREO, etc.) and attracted the attention of a large number of researchers with its powerful energy, dynamics, and variety of observed processes.

In [1], the formation of blobs due to the Rayleigh–Taylor instability in dense coronal ejection material moving through a rarefied corona was considered. The authors of [2] examined the impacts of blobs on the chromosphere. In that study, the velocity of blobs during impact was estimated at 400 km/s, and the plasma density in them was  $5 \times 10^{10}$  cm<sup>-3</sup>. In the subsequent paper [3], the authors identified the trajectories of the blobs as parabolic, their velocity at the time

of impact was 300 to 450 km/s, and their sizes were between 2000 and 4000 km. It was noted that the blobs fell into the chromosphere in two successive streams, and the blobs of the second stream interacted with the shock waves caused by the blobs of the first stream. The authors of [4] studied 16 selected blobs. The estimated masses were in the range  $(1–4) \times 10^{12}$  g, the density was approximately  $5 \times 10^9$  cm<sup>-3</sup>, and the velocity at the time of impact was 230–450 km/s. The rate of the wave rise from the impacts of the first stream of blobs was estimated at 100 km/s. The authors of [5] investigated the deceleration of blobs in the corona. They studied the three-dimensional trajectories of three blobs with sizes of approximately 700 km, and also obtained the estimates of the temperature of their material, approximately 20000 K. In [6], the energy release during the fall of the filament remnants was studied. The velocities of the blobs before impact were estimated at 150–300 km/s. The authors obtained the values of the kinetic energy of blobs at the time of falling in the range of  $7.6 \times 10^{26}$ – $5.8 \times 10^{27}$  erg, and the impact energy released in the form of radiation was  $1.9 \times 10^{25}$ – $2.5 \times 10^{26}$  erg. Finally, in [7], the evolution of the dynamics and density of blobs was analyzed. In that study, the size of the



**Fig. 1.** Propagation of the shock front after a flare. The results of subtraction of the SDO AIA images in the 335 Å Fe XVI line are presented for the following times: (a) 06:23:39–06:22:39; (b) 06:24:39–06:22:39; (c) 06:25:39–06:22:39; (d) 06:26:39–06:22:39; (e) 06:27:39–06:22:39; (f) 06:28:39–06:22:39.

blobs was estimated at 10–20 arcsec (7000–14000 km), the density was  $10^{10} \text{ cm}^{-3}$ , and the mass was approximately  $3 \times 10^{13} \text{ g}$ .

It can be seen that the blob sizes, their velocities, masses, and density obtained by different groups of researchers vary quite significantly, while the temperature estimates are exclusively rarely.

The authors of [8] studied the evolution of NOAA 11226 and the formation of a large filament in it. In [9], the dynamics of the events was examined in a short time interval (approximately 10 min) between the onset of the filament rising and the impulsive phase of the flare. The formation of an EUV wave from an expanding coronal ejection is considered in [10]. In the first 7 minutes of the ejection, it was noted that its velocity increased from 100 to 450 km/s.

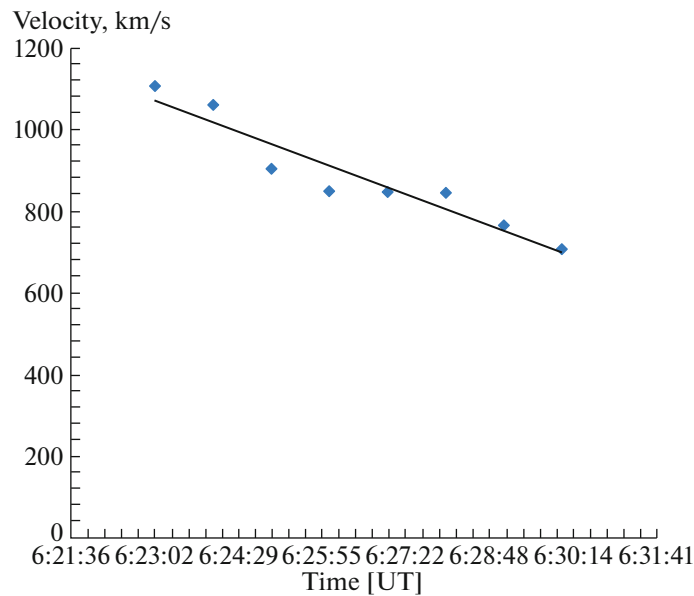
The aim of this study is to analyze, along with spacecraft data (SDO, LASCO), the observations obtained with the horizontal solar telescope spectrograph (HSFA) and multichannel flare spectrograph (MFS) of the Astronomical Institute of the Czech Academy of Sciences in the  $H_{\alpha}$  line of hydrogen and H line of ionized calcium and obtain independent estimations of the kinematic characteristics of the motion of the CME, as well as the velocity of motion of the blob and the physical characteristics of their material.

## 2. OBSERVATIONS AND PROCESSING

This study is dedicated to the analysis of spectroscopic observations of the filament ejection on June 7, 2011 obtained by two ground-based spectrographs: MFS and Horizontal-Sonnen-Forschungs-Anlage 2 (HSFA-2) of the Ondřejov Observatory (Astronomical Institute of the Czech Academy of Sciences). The description of these instruments is given in [11–13]. In addition, we used the data from the SDO and LASCO space telescopes. The considered event is characterized by a sudden filament eruption against the background of an M2.5 flare that occurred at 06:24:15 UT. It was followed by the phenomenon of “coronal rain” and a CME.

### *2.1. Determination of the Velocity of the EUV Wave Front from the Flare*

The propagation velocity of the EUV wave was estimated using SDO AIA observations in the 335 Å Fe XVI line. To determine the position of the front of the EUV wave from the flare, we subtracted the images for selected moments of the flare development. The image obtained at 06:22:39 UT was chosen as the base image. It was subtracted from eight subsequent images obtained with 60 s interval (Fig. 1). Thus, contrast images of the shock front corresponding to eight successive moments were obtained. We measured the variation in the diameter of this front over time and



**Fig. 2.** Velocity of the wave front movement according to the images in the 335 Å line from Fig. 1.

determined the profile of the shock wave propagation speed in the sky plane (Fig. 2).

The graph shows that over the time interval from the first to the ninth minute after the flare, the shock front speed decreased from 1150 to 710 km/s.

### 2.2. Determination of the Velocity of the Prominence Ejection from Ground-Based Observations

The images of the filtergram with the position of the spectrograph slit-jaw (SJ) and the spectrum in the  $H_{\alpha}$  line obtained at the MFS at 06:40:32 UT are shown in Fig. 3. The vertical line in the SJ image corresponds to the position of the spectrograph slit. Two horizontal threads define the scale of the image. The spatial and temporal resolutions are 0.3"–0.5" and 30 s, respectively.

A total of 33 spectra of the erupting prominence in the  $H_{\alpha}$  line for 22 moments in the interval 06:40–07:40 UT were selected for processing. A feature of the prominence with the maximum deviation of the center of the line both toward the red and blue parts of the spectrum was selected in each spectrum. These deviations were used to calculate the line-of-sight velocities of these features (Fig. 4). The maximum values turned out to be 190 km/s (shift toward the red part of the spectrum) and –200 km/s (shift toward the blue part of the spectrum).

If we analyze the time variation of the radial velocity of those “fastest” features of the prominence, we can estimate the maximum acceleration (along the line of sight) with which this prominence moves. For red shift, this acceleration is 0.124 km/s<sup>2</sup>, for blue shift it is –0.032 km/s<sup>2</sup>. Note that these values are signifi-

cantly less than solar gravitational acceleration (0.265 km/s<sup>2</sup>). Thus, it can be assumed that there is a mechanism that slows down the fall of the erupted prominence material onto the chromosphere.

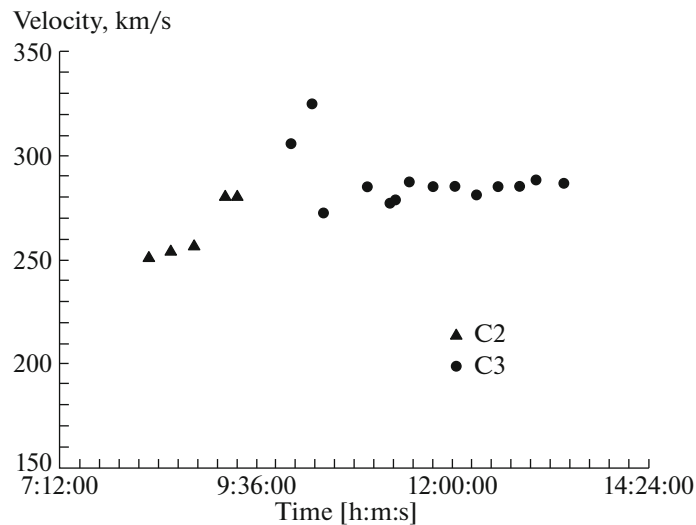
### 2.3. Determination of the Velocity of the Prominence Ejection from Space Observations

Using the data from the LASCO spacecraft (instruments C2, C3), we determined the variation in the position of the upper boundary of the outgoing prominence or CME over time in the interval 08:17–13:21 UT (08:17–09:21 UT from the C2 data and 10:01–13:21 UT from the C3 data). A diagram of the coronal ejection velocity was constructed based on these data (see Fig. 5). The diagram shows two phases of the CME motion. In the first phase, the material moves with acceleration, and its velocity in 64 min increased from 252 to 281 km/s. In the second phase, the velocity of matter almost did not change and it was 285 km/s. The scatter of the velocity values in the interval 10:01–10:30 UT can be explained by the small scale of the C3 image and, therefore, the large error in determining the CME boundary displacement at small distances from the solar disk.

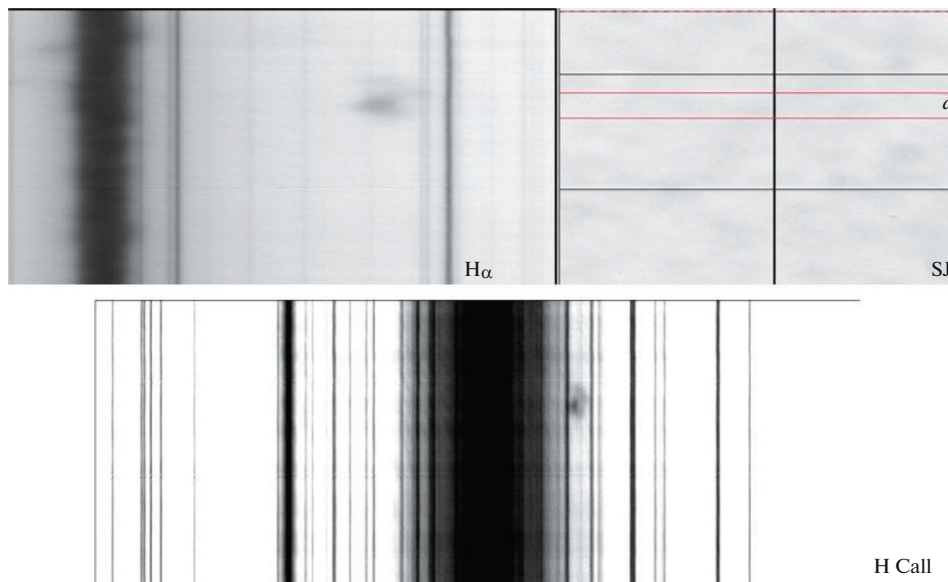
### 2.4. Determination of the Velocity Profile of an Incident Filament Fragment (Blob) from Spectral Ground-Based Observations

Simultaneously with the observations at the MFS, the observations at the Ondřejov Observatory were carried out at the HSFA-2. This spectrograph allows obtaining spectra in the  $H_{\alpha}$ ,  $H_{\beta}$ , Ca II (H or K), Ca IR 8542 Å, and D3 lines with high spatial and temporal





**Fig. 5.** Results of the CME velocity measurements according to the LASCO C2 and C3 data in the interval 07:46–13:12 UT. The triangles indicate the C2 data, the circles indicate the C3 data. The C3 plot shows the constancy of the ejection velocity after 11:17:36 UT.



**Fig. 6.** Example of the observational data from the HSFA-2 spectrograph. Time point 08:06:14 UT. The picture shows the spectrum in the  $H_{\alpha}$  line, filtergram of the chromosphere in the  $H_{\alpha}$  line with the position of the spectrograph SJ, and spectrum in the H Ca II line. The dark formation in the spectra corresponds to the falling fragment of the prominence, or blob. The region of the photometric section is marked in the SJ image as (a).

falling linearly increased from 207 to 263 km/s over 5 min.

### 2.5. Determination of the Physical Parameters of an Incident Plasma Fragment (Blob)

Knowing the image scale in the SJ images and H Ca II and  $H_{\alpha}$  spectra, we estimated the size and mass of the blob for the time of observation at 08:06:14 UT:

$d = 5900$  km,  $m = 1.8 \times 10^{12}$  g. To determine the mass, we used the estimate of the density in the filament  $10^{10}$  cm $^{-3}$  under the assumption that the blob is spherical.

After the photometric processing of the spectra (Fig. 8), we obtained the profiles of the spectral lines H Ca II and  $H_{\alpha}$  (Fig. 9) corresponding to the absorption of radiation in the blob. The  $H_{\alpha}$  line and the cen-

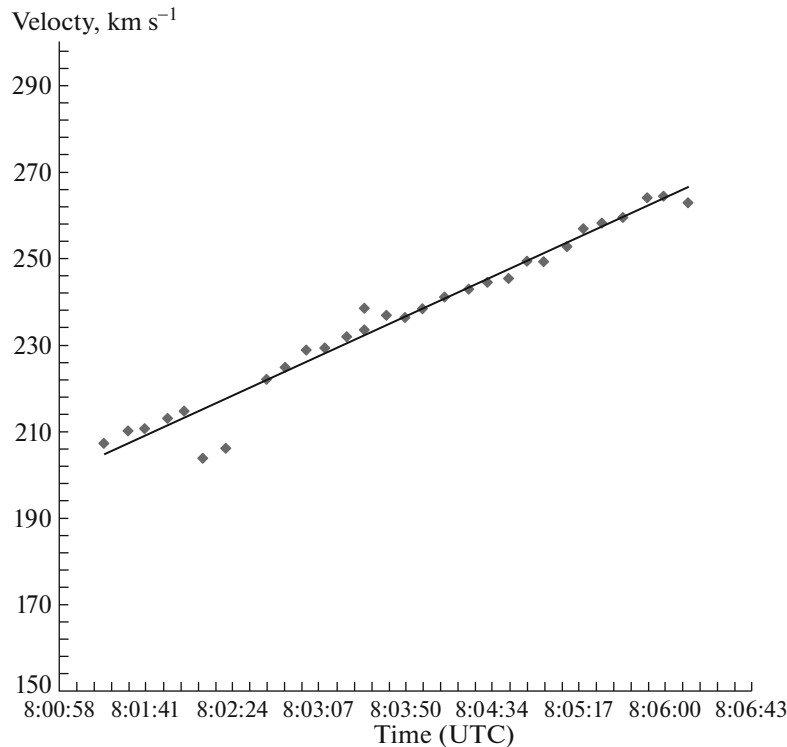


Fig. 7. Velocities of the blob fall measured from the shift of the  $H_{\alpha}$  line in the HSFA-2 spectra in the interval 08:01–08:06 UT.

tral part of the H Ca II line are well fitted by Gaussian profiles. This fact indicates that the blob material has small optical thickness. The measured Doppler half-widths of the lines were  $\Delta\lambda_{D H_{\alpha}} = 0.480 \text{ \AA}$ ,  $\Delta\lambda_{D CaII H} = 0.249 \text{ \AA}$ . In view of the compactness of the object and its small optical thickness in the lines under study, it can be assumed that the absorption in H Ca II and  $H_{\alpha}$  is localized in one place. Assuming the Doppler line broadening as a result of the combination of the thermal motion of absorbing atoms and microturbulence in the blob material, we obtain the corresponding values of temperature and turbulent velocity:

$$\Delta\lambda_D = \frac{\lambda_0}{c} \sqrt{\frac{2kT}{m} + V_{\text{turb}}^2},$$

$$T = 7880 \text{ K}, \quad V_{\text{turb}} = 18.7 \text{ km/s}.$$

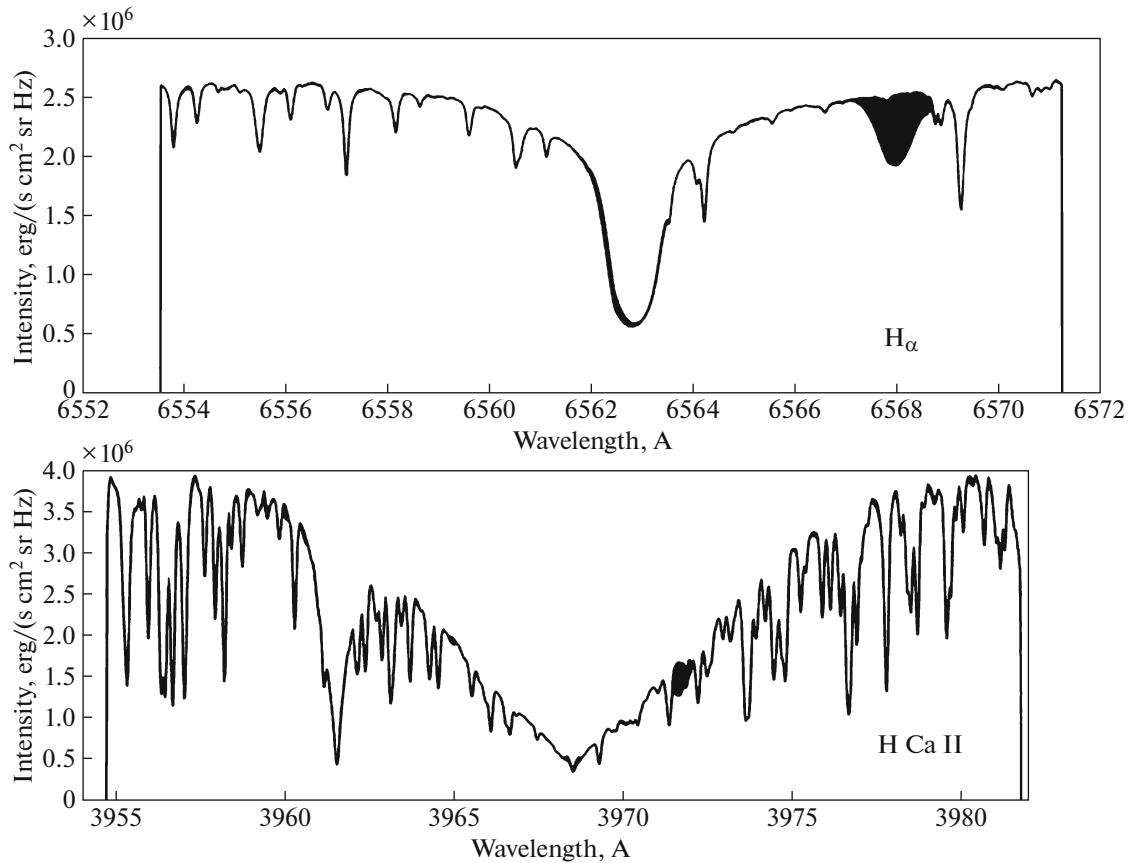
With an accuracy of determining the Doppler line width of  $0.005 \text{ \AA}$ , the error in calculating the temperature is 1500 K, and the error in the microturbulence velocity is 0.4 km/s. The main contribution is made by the error in determining the Doppler width of the H Ca II line. It can be seen that the temperature is more sensitive to error than  $V_{\text{turb}}$ .

### 3. DISCUSSION AND CONCLUSIONS

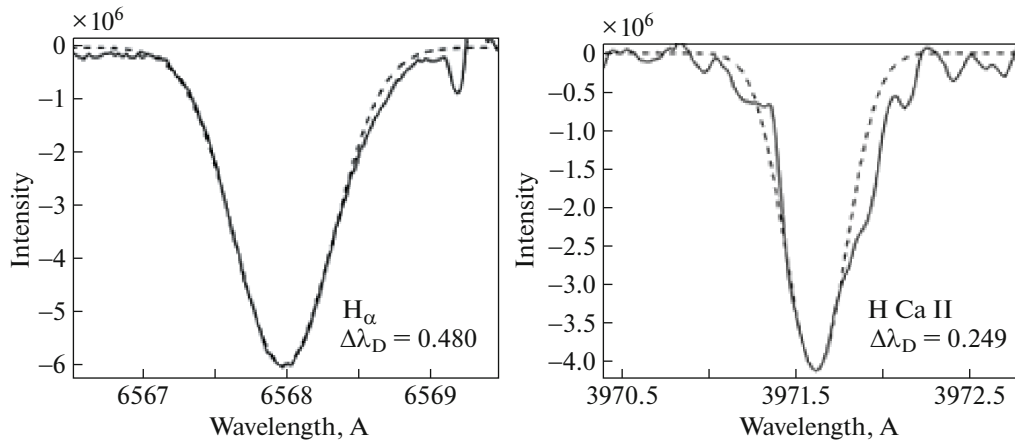
We have carried out a study of the parameters of blobs, compact fragments of the ejection matter that

fell back into the chromosphere; they were observed during the ejection of a filament on June 7, 2011. The studies of the shock wave propagation velocity based on the observations in the  $335 \text{ \AA}$  line showed the deceleration of the CME. This was also confirmed by independent ground-based observations in the  $H_{\alpha}$  line, which indicated that the acceleration of the ejected filament (in the red wing of the line) was significantly smaller than the acceleration of gravity. Note that we have found the acceleration in the blue wing to be also significantly smaller than the acceleration of gravity, which indicates that the fall of matter into the chromosphere was determined not only by the force of gravity.

The blob drop velocity (207–263 km/s) determined by us from the optical ground-based observations is in good agreement with the estimated ones by other authors [3, 4, 6] obtained from the spacecraft data: 150 to 450 km/s. It should be noted that modern solar spectrographs and filters cannot detect high velocities in eruptive events due to the limited wavelength range in instruments with high spectral resolution. Possible high velocities in chromospheric lines in the impulsive phase of the flare and before could exist, but could not be measured. However, in this case, the velocities of the eruptive material at the later stages of evolution, measured both by ground-based spectrographs and from the data of the LASCO coronagraph, coincide. This fact and the agreement with the results



**Fig. 8.**  $H_{\alpha}$  and H Ca II line profiles in the falling fragment of the prominence and the adjacent region of the chromosphere. Absorption in the blob is marked with dark color.



**Fig. 9.**  $H_{\alpha}$  and H Ca II line profiles corresponding to absorption in the blob (solid lines) and their approximation with Gaussian curves (dashed lines).

of other authors gives us the reason to assume that our estimates are correct.

The blob size that we obtained from the spectrum in  $H_{\alpha}$ , was 5900 km. This is considerably higher than

the value obtained in [5] (700 km), but is in good agreement with the results of [3] (2000 to 4000 km) and [7] (7000–14000 km). Assumed by us value of the blob density of  $10^{10} \text{ cm}^{-3}$  is also in agreement with the

estimations of other authors [2, 4, 7]. Thus, we can conclude that our estimate of the blob mass at  $1.8 \times 10^{12}$  g is quite reasonable. The physical parameters of the blob material obtained from independent observations—a temperature of 7880 K and a turbulent velocity of 18.7 km/s—are quite consistent with the characteristic parameters of the filaments [14]. This fact indicates the origin of the blob, as well as the fact that one of the possible reasons for the “slow” fall of the blob could be its connection with the structure of the magnetic field of the filament, which was not completely destroyed during the eruption.

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